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Short communication

Irrigation of 'Green walls' is necessary to avoid drought stress of grass vegetation (*Phleum pratense* L.)

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ABSTRACT

Climate change will lead to increased frequencies of weather extremes in Central Europe, such as severe heat waves and droughts, causing high stress intensities for plants. Drought stress also represents a critical factor on many re-cultivated areas with poor edaphic conditions and small soil depths. This includes living wall systems which are applied to cover shotcrete walls and re-integrate them in landscape surroundings. Due to the vertical arrangement of these systems, which limits absorption of rain water, artificial irrigation was considered mandatory, but experimental evidence is lacking. Therefore, we compared soil and plant water relations of test plots on a 'Green wall' system with active and deactivated irrigation. During the vegetation period 2017, soil water potential and plant hydraulic parameters (stomatal conductance, relative water content, midday leaf water potential and osmotic potential) of *Phleum pratense*, the dominating grass on study plots, were measured.

In summer 2017, many weeks with humid weather conditions, but also a pronounced heat period were registered. During this period, considerable physiological responses were observed and respective recovery after subsequent days of heavy precipitation. *Phleum pratense* showed reductions in stomatal conductance ($-148.6 \pm 118.8\ mmol m^{-2} s^{-1}$), relative water content ($-9.3 \pm 10.1\%$) and midday leaf water potential (-0.3 ± 0.5 MPa) on the test plot during heat days. Upon precipitation, differences in water relations between plots ceased within few days. Results indicate that integrated irrigation systems are a necessary component of living wall systems.

1. Introduction

Water is the central molecule in all physiological processes and the major medium for transporting metabolites and nutrients (Araya and Garcia-Baquero, 2014; Lisar et al., 2012). On drought and respective water deficits, plants may thus be exposed to severe or even lethal stress levels (Signarbieux and Feller, 2012; Lisar et al., 2012). Drought stress may develop slowly over weeks or months but can also occur as short-term water deficit within hours to days (Chaves et al., 2003; Reynolds-Henne et al., 2010). Adaptions conferring drought resistance involve a mixture of stress avoidance and/or tolerance strategies (Chaves et al., 2002; Osmond et al., 1987). Drought avoidance is based on mechanisms that minimize water loss from plants by changes in e.g. stomatal conductance, leaf area or leaf orientation (Farooq et al., 2009; Touchette et al., 2007). Stomatal closure, together with leaf growth inhibition, are among the earliest responses to drought, protecting the plants from extensive water loss (Chaves et al., 2003). According to Signarbieux and Feller (2012), annual plant species in grassland ecosystems are typical stress avoiders reducing activity during extreme stresses or becoming dormant (Osmond et al., 1987). Tolerance mechanisms take over when tissues are no longer protected by avoidance mechanisms and are usually found in xerophytes. Examples are reduction in water loss by increasing stomatal resistance, increased water uptake by developing large and deep root systems, accumulation of osmolytes and osmoprotectant synthesis (Farooq et al., 2009).

Drought stress also represents an essential factor on restoration areas because of extreme microclimatic and edaphic conditions. Soil moisture conditions on these sites are usually insufficient due to small soil depths, which makes an appropriate drought tolerance of planted species crucial for successful restoration of drought prone sites (Beikircher et al., 2010). This also applies to the restoration of steep slopes (i.e. living walls), like shotcrete walls. Resulting from the vertical arrangement, enhanced surface runoff and lack of connection to the natural soil, drought and temperature stress (with high temperature variations and high temperature extremes) are the most limiting factors on these sites for plant establishment. Recently, a new approach to

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integrate shotcrete walls into the natural surroundings by using an innovative vertical living wall system (hereinafter referred to as 'Green wall'), which consists of two components (a double-layered steel grid construction and a vegetation layer; Medl et al., 2017a,b), was developed. For static and economic reasons, the volume of soil substrate used as growth medium for plants in living walls is usually limited and water retention properties are respectively low (Pitha et al., 2011). On steep surfaces, moisture received from precipitation or external irrigation quickly drains, which only allows very low absorption of water (Access irrigation, 2015). Thus, only the water retained by the substrate is available for plants, which makes it necessary to keep the substrate permanently wet for sufficient plant growth and establishment (Pérez-Urrestarazu et al., 2014). Hence, integrated watering systems, which enable a complete irrigation of living wall systems, are considered mandatory in these kind of systems. Usually, irrigation requirements are highly variable and depend on several factors such as type of system, light exposition, temperature and humidity conditions as well as vegetation and substrate used (Pérez-Urrestarazu et al., 2014; Manso and Castro-Gomes, 2015). One of the most common ways of irrigation is the installation of drip lines at different heights so that water can move vertically and laterally in between lines by gravity and lateral diffusion (Pérez-Urrestarazu et al., 2014). Though, as stated by Hunter et al. (2014), most studies only state the 'adequate supply of moisture', while detailed experiments on the necessity and extent of irrigation intensity are widely lacking. Table 1 gives an overview on several current studies containing information on irrigation systems and frequencies.

Ottelé et al. (2011) expect a necessary replacement of watering systems in green walls every 7.5 years due to crystallizing of salts. Thus, besides costs for the installation of irrigation systems, the effort in case of replacements and the costs for running the system have to be considered, and the costs for living walls might be much lower when irrigation systems could be omitted.

The aim of the reported study was (i) to scrutinize the necessity and efficiency of an integrated watering system, (ii) to analyse potential changes in vegetation performance on the 'Green wall' after irrigation stop and (iii) to estimate the drought resistance of 'Green walls' during heat waves. We measured stomatal conductance, relative water content, midday leaf water potential and osmotic potential of *Phleum pratense* in July/August 2017 over a period of six weeks on a 'Green wall' test plot with deactivated irrigation in comparison with an irrigated reference plot. Additionally, microclimatic conditions of soil (soil water potential) and meteorological data (precipitation, air temperature) were monito.

2. Material and methods

2.1. Experimental design

A shotcrete wall along the Brenner Highway located in Plon, Steinach am Brenner (Tyrol, Austria, 1048 m asl, 47°6′N, 11°28′O) was selected for the *in situ* experiment. The test field (Fig. 1) was installed in July 2016 using the 'Green Wall' system consisting of a double-layered steel grid construction (Krismer GmbH, Rum, Austria) with a layer dimension of 16 cm (8 cm each layer). First and second layers were assembled to the wall using threaded rods to be manually filled with a mixture of rock material and compost serving as substrate material, while drip tubes (drip distance 33 cm, 2 L/h) for automatic irrigation were installed in-between. After the application of seed mixture by means of hydroseeding, a synthetic geotextile was applied as protection layer.

2.2. Drought experiment

The test field contained two separate water circuits (Fig. 1). Circuit No.1 was turned off on 17 July 2017, while the reference plot (Circuit No.2) was still automatically irrigated 4 times per day (3.30 min each, 2 L/h). In order to simulate real conditions in the event of irrigation failure, no measures were taken against natural precipitation.

2.3. Climatic measurements

A climate station in close proximity to the test field delivered standard meteorological data. Campbell CS215 (accuracy ± 4% and ± 0.9 °C) was used to record air temperature, precipitation was captured by Campbell Bucket Raingauge 52203 (0.1 mm/tip). Measurements were taken in 1-min intervals and 10-min means stored.

Microclimatic data logger instrumentation installed in the soil provided information about soil water potential (EMS MicroLog SP3) on the experimental site. Four data loggers (Fig. 1; three sensors each; accuracy ± 2.0%) were mounted in the soil substrate (10 cm depth) of the 'Green wall', two in the test plot (TP_1, TP_2) and two in the reference plot (RP_1, RP_2). Three sensors (No.1, No.2 and No.3) per data logger were installed at three different heights (0.5 m, 1.5 m and 2.5 m). Measurements were made in 10-min intervals.

2.4. Physiological measurements

Phleum pratense L. is a grass species, commonly used for restoration works (Isselin-Nondedeu and Bédécarrats, 2009) with sufficient size for physiological measurements. It dominated the experimental sites and thus was chosen for investigations during the drought experiment. The physiological response of *Phleum pratense* to drought stress was evaluated by measuring stomatal conductance of leaves, relative water content, midday leaf water potential and osmotic potential. Measurements were carried out on 6 days (19, 20 July, 3, 7, 21, 24 August) during noon, when solar radiation was highest. Leaves for water content and potential measurements were taken at a height between 1.5 and 2.0 m of the living wall system. To prevent transpiration after sampling, leaves were wrapped into aluminium foil and plastic bags for transportation to the laboratory.

Table 1
Overview on irrigation management of selected studies.

No.	Source	Location	Vegetation	Irrigation system	Irrigation frequency
(1)	Cheng et al. (2010)	Hong Kong	Grass	Irrigation pipeline	Twice a day
(2)	Chen et al. (2013)	China	Not defined	Sprinkler system	Once a day
(3)	Coma et al. (2017)	Spain	Evergreen	Drip line	Daily
(4)	Djedjig et al. (2017)	France	Not defined	Drip line	Twice daily (5 min)
(5)	Mazzali et al. (2013)	Italy	Evergreen and perennial	Drip line	Not defined
(6)	Olivieri et al. (2014)	Spain	Sedum	Drip line	Not defined
(7)	Ottelé et al. (2011)	Netherlands	Fern	Drip line	Not defined
(8)	Razzaghmanesh and Razzaghmanesh (2017)	Australia	Perennial	Drip line	Not defined
(9)	Scharf et al. (2012)	Austria	Perennial	Drip line	According to demand
(10)	Serra et al. (2017)	Italy	Evergreen and perennial	Drip line	Every two hours (2 min)

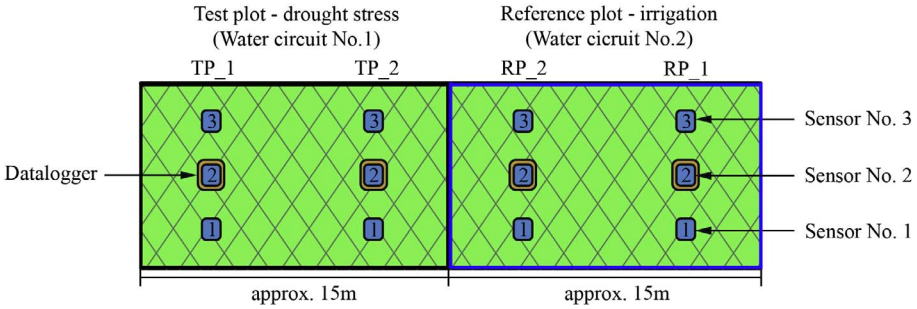

Fig. 1. Schematic figure of test field and experimental design.

2.4.1. Stomatal conductance (g_s)

g_s of *Phleum pratense* was determined in the field using a porometer (Leaf Porometer SC-1, Decagon Devices). Analysis of g_s were made on 12 individuals per plot, and mean values were calculated.

2.4.2. Relative water content (RWC), midday leaf water potential (ψ_m) and osmotic potential (ψ_π)

After the collection of plant material on-site, fresh weight (FW), saturation weight (SW, after full saturation for 24 h) and dry weight (DW, after drying for 24 h at 100 °C) of six samples per plot were gravimetrically determined in the laboratory (Sartorius BP61S; 0.0001 g precision). RWC (%) was calculated according to the following equation (Pallardy et al., 1991).

$$RWC = \frac{FW-DW}{SW-DW} \cdot 100 \quad (1)$$

ψ_m of *Phleum pratense* was measured on seven individuals per plot using a Scholander pressure chamber (PMS Instrument Company, Model 1505D). For determination of ψ_π, leave tissues were frozen in the freezer and subsequently thawed to disrupt cells. Leaves from seven individuals were pooled in a leaf press and the sap squeezed on a filter paper. The average of three ψ_π measurements (vapor pressure osmometer; VAPRO 5520, Wescor, Inc.) of the sap samples was taken, respectively. Five samples per measurement date were analysed and the mean calculated.

2.5. Statistical analysis

For all physiological parameters (g_s, RWC, ψ_m and ψ_π) differences between the non-irrigated and the reference plot were tested ($p < .05$) via t-tests. Boxplots were created for graphical display. All statistical analyses were performed using IBM SPSS Statistics 21.

3. Results

3.1. Climatic measurements

Fig. 2 illustrates air temperature and precipitation during the measurement period from 17 July to 24 August 2017. The longest period without remarkable precipitation was recorded between 25 July and 3 August (mean daily sum of precipitation 1.4 ± 1.5 mm, daily mean temperature 16.9 ± 5.0 °C). During this period, air temperature reached a maximum of 29.8 °C on 3 August. This heat event was directly followed by several days of heavy rainfall (mean daily sum of precipitation 4–11 August: 21.3 ± 10.6 mm), which were coincidently accompanied by lower air temperatures (daily mean temperature 15.5 ± 3.7 °C).

3.1.1. Soil water potential (ψ_s)

Fig. 3 shows the course of ψ_s within the measurement period from 17 July to 24 August 2017. Sensors No. 2 were selected for graphical display (see Fig. 1, same height as physiological measurements). TP_1 and TP_2 decreased below −1.4 MPa (minimum measurement range of dataloggers) between 2 and 7 August, while RP_1 and RP_2 were constantly around −0.01 MPa during the whole measurement period except for 24 July, when RP_1 reached its minimum ψ_s of −0.1 MPa. Thus, the measured values indicate a desiccation of the test plot from late July on and an intense drought period in the first week of August, while the reference field was constantly saturated from 17 July to 24 August.

3.2. Physiological measurements

3.2.1. Stomatal conductance (g_s)

Porometer measurements (Fig. 4A) revealed significantly lower g_s on the test plot than on the irrigated reference plot. Differences were highest on 3 August with an average conductivity of 65.2 ± 19.0 $mmol\,m^{-2}\,s^{-1}$ on the stressed test plot versus 213.7 ± 109.6 $mmol\,m^{-2}\,s^{-1}$ on the saturated reference plot. When comparing the days before (19 and 20 July) and after (21 and 24 August) the heat event, it is evident that g_s on the test plot as well as on the reference plot was much higher before the heat wave. This also applies to the differences in g_s between test plot and reference plot.

3.2.2. Relative water content (RWC), midday leaf water potential (ψ_m) and osmotic potential (ψ_π)

RWC was similar at the beginning and end of the experiment, while pronounced differences were detected during the drought period. On 3 August, (Fig. 4B) RWC at the test and reference plots were 78.4 ± 7.6% and 87.7 ± 5.4%, while on 7 August, 87.7 ± 5.2% and 84.7 ± 8.5% were measured, respectively.

Potentials were also similar during most of the vegetation period, except for the time during the heat wave. On 3 August, ψ_m (Fig. 4C) was

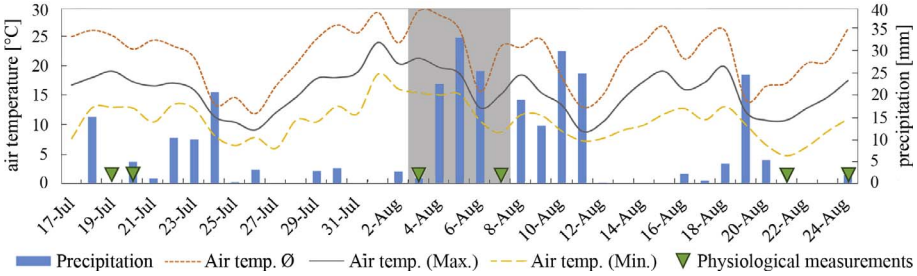

Fig. 2. Daily mean, minima and maxima of air temperature and precipitation from 17 July to 24 August. Days of physiological measurements are marked with green triangles. The grey area highlights the interesting drought period and subsequent rainfall from 3 to 7 August.

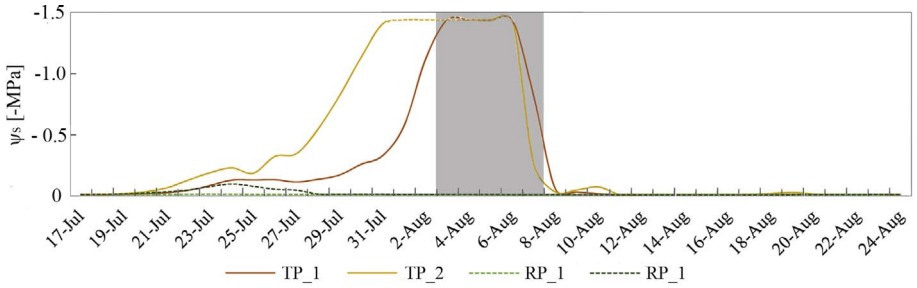

Fig. 3. Mean ψ_s from 17 July to 24 August. The grey area highlights the period of interest from 3 to 7 August.

more negative on the test plot (−2.07 ± 0.55 MPa) than on the reference plot (−1.78 ± 0.16 MPa). On 7 August, after the rainy days, values of ψ_m were overall less negative (test plot −1.40 ± 0.21 MPa; reference plot −1.09 ± 0.36 MPa). Differences in ψ_π (Fig. 4D) were also significant during the drought period. On 7 August, ψ_π on the test plot was −1.20 ± 0.06 MPa, while on the reference plot −1.01 ± 0.02 MPa was observed.

4. Discussion

Living walls represent extreme sites with respect to the steep slope, limited soil volume and potential drought stress. Up to now, detailed experiments on the necessity and extent of irrigation intensity are widely lacking (Table 1). Thus, this study was conducted to scrutinize the central role of an integrated watering system in the 'Green Wall' (Medl et al., 2017a). Although only one, relatively short drought period occurred during the experiment, physiological measurements indicated drought stress at a non-irrigated test plot compared to an irrigated reference plot (Fig. 1).

While measured parameters were similar on the test and the reference plot during the first weeks of the experiment, significant physiological responses to the drought/heat period from 25 July to 3

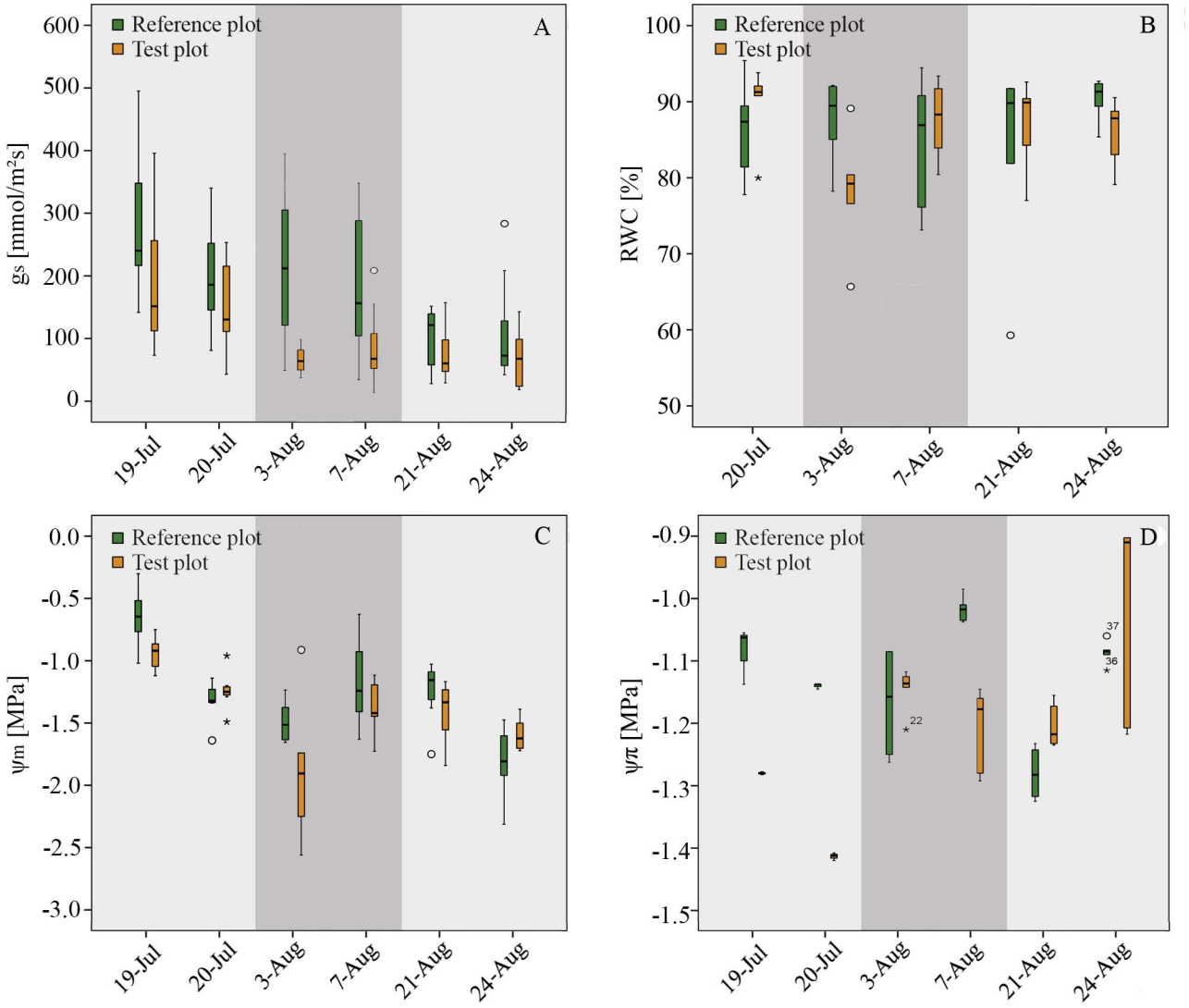

Fig. 4. Recorded margins (calculated with SPSS) of stomatal conductance (g_s), relative water content (RWC), midday leaf water potential (ψ_m) and osmotic potential (ψ_π) of *Phleum pratense*.

August (Fig. 2) were registered. Soil water potential (ψ_s) of the non-irrigated test plot became more negative with the beginning of the drought/heat period (Fig. 3). Minimum ψ_s on the test plot was reached between 3 and 6 August, while the irrigated reference plot remained at moderate potentials. Remarkable, ψ_s rapidly increased from 6 to 7 August upon the consecutive rainy period indicating the 'Green Wall' to re-saturate quickly after days with strong precipitation. Since our data give no indication about the amount of absorbed precipitation, surface runoff and saturation depth, a quantification of the water retention capacity is not possible.

Stomatal closure upon drought is probably the most sensitive and earliest stress indicator, and g_s thus more strongly affected than any other components in plant water relations (Chaves et al., 2002; Farooq et al., 2009; Smith and Hollinger, 1991). Accordingly, our experiment showed that g_s of *Phleum pratense* under drought conditions decreased almost in parallel to decreasing soil water potentials and displayed significant differences to plants growing at the irrigated reference plot (Fig. 4A). *Phleum pratense* reached a ψ_m of ca. −2.5 MPa at a minimum (Fig. 4C), which might be critical regarding cell turgor and xylem embolism, and the grass thus reduced g_s. These results confirm findings of Signarbieux and Feller (2012), who found ψ_m values of -2.42 ± 0.03 MPa in *Phleum pratense* after several weeks of artificial drought. They also demonstrated respective stomatal response to low water potentials, as g_s was reduced from 325.0 ± 30.8 to 224.0 ± 17.3 mmol$m^{-2}s^{-1}$ upon drought. The drought/heat period of the present study and in the study of Signarbieux and Feller (2012) thus led to photosynthetic limitation of *Phleum pratense*, and it is likely that prolonged drought/heat would also cause severe drought damage.

During the drought/heat period in July 2017, we also observed a decrease in RWC (Fig. 4B). Accordingly, differences in ψ_π were probably passive effects of solutes, up-concentrated in dehydrated leaf tissues. Though, ψ_π of *Phleum pratense* at the non-irrigated test plot showed a pronounced seasonal course and an increase during the first weeks in August (Fig. 4D). This indicates plastic adjustment of ψ_π under irrigated conditions, while grass specimens on the non-irrigated plot were forced to keep low ψ_π, probably to maintain leaf turgescence.

Hitherto, research activities in plant hydraulics mainly focussed on woody species, while information on grass hydraulics is scarce. However, it can be assumed that the general drought resistance and drought adjustments are species-specific, as e.g. demonstrated in studies on *Lolium multiflorum*, *Trifolium repens*, *Rumex obtusifolius* or *Ranunculus* species (Signarbieux and Feller, 2012; Nolf et al., 2016). Accordingly, Signarbieux and Feller (2012) observed differences concerning drought effects between the dicotyledonous species *Trifolium repens* and *Phleum pratense* as well as *Lolium multiflorum* indicating a higher drought tolerance of forb and legume species. Nolf et al. (2016) demonstrated that *Ranunculus* plants can adjust to their habitat conditions on interspecific and intraspecific levels in various hydraulic parameters. Thus, use of more drought resistant plants might be useful to establish a vegetation cover on living walls at dry sites. The experiment of the presented study was consciously performed on *Phleum pratense* to test the necessity of irrigation on a species widely used for greening approaches. Observed drought stress, even at the relatively humid experimental site and during a relatively short and mild drought, indicated that irrigation systems are necessary, at least when greening is based on standard seed mixtures. This is especially relevant with respect to future reduction in summer precipitation and more frequent heat waves, as predicted by climate models. The use of species-rich seed mixtures in combination with efficient irrigation systems may help to establish and maintain sustainable vegetation layers on vertical greenery systems. More and especially long-term studies are required to further optimize living wall systems.

5. Summary

Hitherto, artificial irrigation of living walls was considered mandatory. In this study, 'Green wall' plots, dominated by *Phleum pratense*, with integrated watering system and without irrigation were compared to test possible drought stress. Measurements indicated that lack of irrigation on the vertical greening system affects the vegetation cover during drought periods.

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